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THE RE-EVALUATION OF HEAT BALANCE IN LAKE VANDA, VICTORIA LAND, ANTARCTICA

By

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Abstract

The heat balance of Lake Vanda, Victoria Land, Antarctica in 1971–72 austral summer season is evaluated. Terms of heat gain consist of solar and sky radiation and sensible heat exchange with atmosphere, and geothermal activity or influx of thermal waters are not detected. Solar radiation is consumed as follows; reflection 39.8%, internal melting of lake ice 3.6%, penetration through lake ice 6.9%, and 49.7% for evaporation and back radiation. Apparent heat transfer coefficient in the upper layer of the lake is about 6 times of molecular diffusivity, and is related with the step-like structure of water temperature profile.

1. Introduction

Lake Vanda (77°35′ S., 161°39′ E.) occupies the lowest part of Wright Valley, Victoria Land, Antarctica. It is 5.6 *km* in length, 1.4 *km* in width, and has a surface area of $5.43 \times 10^6\ m^2$. Its maximum depth is about 65 *m*. The lake has no outflow and is supplied by the Onyx River which runs from the end of the Lower Wright Glacier towards inland gathering melting waters of surrounding glaciers in the austral summer season, and is also a permanently ice-covered lake, except for a narrow band of free water along the lake shoreline in summer. Water temperature is 0°*C* just below the lake ice but rises to about 25°*C* near the lake bottom. The vertical profile of water temperature shows a step-like structure, in which layers of homogeneous temperature (convecting layer) and sheets of sharp temperature gradiant appear by turns, in the upper part of the lake. In the middle part, a large convecting layer (about 20 *m* in thick) is predominant. Below this layer, the step-like structure reappears again and water temperature profile becomes a smooth curve going below 50 *m* in depth. Concentrations of chemical elements (main constituents are Ca^{++} for cation and Cl^- for anion) increase downward, and its vertical profile shows a step-like structure in correspondence to the temperature rise. The electrical conductivity of the water at the bottom is surprisingly high of $1.2 \times 10^5\ \mu\mho/cm$ at 18°*C*. Thus the water at the bottom has the highest density of about $1.09\ gm/cm^3$ in spite of the high temperature.

It is a wonder that there is such water showing high temperature in an area of cold climate (annual mean air temperature is about −20°*C*), and many investigators have considered and discussed about the origin of heat. Angino et. al [1963, 1965] concluded the heat origin as a geothermal activity and/or an influx of thermal waters, based on their observation of the thermal dome near the center of the lake, and they also suggested that some chemical constituents of the lake water are similar to those of thermal waters in hydrothermal areas.

Wilson and Wellman [1962] found that the temperature gradient versus the depth profile is as would be expected from a solar heating mechanism, and contradicted the idea of an influx of thermal waters or geothermal activities.

Ragotzkie and Likens [1964], however, suggested that the effect of heat supply through the lake bottom into the lake water cannot be ignored on the basis of the heat balance study made in the summer of 1962–63. Their heat balance evaluation is useful for understanding thermal characteristics of ice-covered lakes in polar regions, but their findings may not so accurate because of lack of detailed data.

The step-like structure of temperature and salinity in Lake Vanda provide an important example for the diffusion process of a two-components system under the circumstances in which both elements are increasing downward. Though the step-like structure may be explained by the idea of thermo-haline convection (Hoare [1968]), it was not clear what is the heat origin maintaining the convective motion.

This paper will present a re-evaluation of heat balance in Lake Vanda on the basis of new data, and clarify the origin of this heat.

Observations were carried out in the two austral summer seasons of 1970–71 and 1971–72, and methods and results have been published saperately (Yoshida et. al [1971], Torii et. al [1972]).

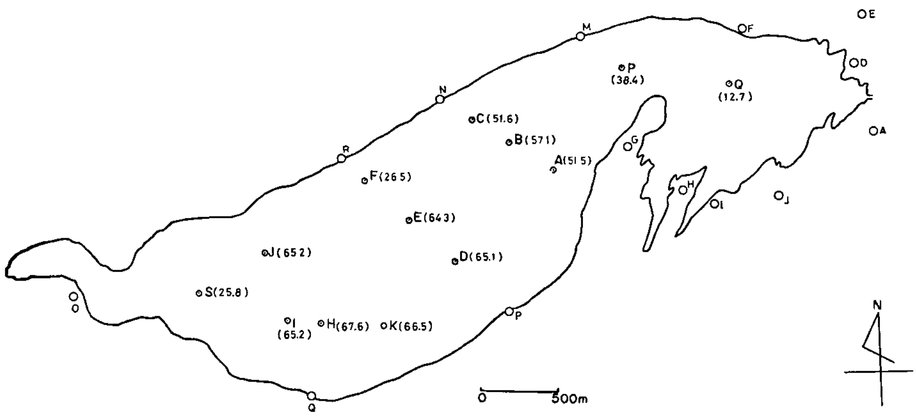

Fig. 1. Location of observation station. Figures in paretheses indicate depth in metres (2–4 January 1972).

2. Heat balance

Expressing heat gain terms of water body as positive value, and heat loss and storage terms as negative, the classical heat balance equation is written as follows:

$$Q_i+Q_e+Q_a+Q_c+Q_v+Q_f=0, \tag{1}$$

where Q_i : net flux radiation on the lake
Q_e : heat loss by evaporation
Q_a : sensible heat exchange with the atmosphere
Q_c : heat exchange through the lake bottom
Q_v : change of heat storage
Q_f : heat exchange by advection

In this section, we will estimate each value of above terms in an ice-covered lake following the example of Lake Vanda, the 1971–72 austral summer season, when observations were most precisely carried out.

(*A*) *Net flux radiation*

Since 1968, the New Zealand Antarctic Programme (NZARP) has carried on meteorological observations including radiation measuremens at Vanda Station, which was erected on the lakeside. Fortunately, it has become possible to obtain various data on radiation, such as solar radiation and albedo etc., in this area precisely. In 1971–72 summer season, the Japanese Dry Valley Party (JDVP) also measured solar radiation at the point about 1.5 *km* west from Vanda Station, and results were almost identical with those obtained at Vanda Station. Here, we will estimate net flux radiation on the lake ice basing on Vanda Station's data.

Net flux radiation on ground surface (N) may be represented as

$$N=I_s(1-\alpha_e)+I_l-s_e\sigma T_e^4, \tag{2}$$

where I_s and I_l are solar and sky radiation, α_e, s_e and T_e are albedo, emissivity and temperature of ground surface respectively, and σ is Stefan-Boltzmann's constant.

It may be not unreasonable to assume that sky radiation has the same value on the lake ice and surrounding area of the lake. Therefore, net flux radiation (Q_i) will be given by

$$Q_i=I_s(1-\alpha_i)+I_l-s_i\sigma T_i^4, \tag{3}$$

where α_i, s_i and T_i are albedo, emissivity and temperature of ice surface respectively. Eliminating I_l in Eqs. (2) and (3), Q_i is expressed as

$$Q_i=N+I_s(\alpha_e-\alpha_i)+s_e\sigma T_e^4-s_i\sigma T_i^4. \tag{4}$$

We assume that emissivities, s_e and s_i, are same value of 0.9 which is average value of various earth surfaces.

Albedo on the ground surface, α_e, was measured at the neighbourhood of the observation point of net flux radiation by NZARP, and mean value is 0.21 (Thompson et. al [1971]). On the contrary, α_i takes various values with changing of the ice surface conditions. According to observations in 1970–71, it was almost constant before November when air temperature was below 0°C, and the mean value is 0.33.

However, α_i increased in process of the season, and the highest value was 0.55 on January 1971. In 1971–72 season, α_i on the permanent ice had relatively wide range of 0.32 to 0.53, after air temperature rose up to above 0°C, and its weighted mean value was about 0.40.

We will use temperature at 8 *cm* depth below ground surface observed at Vanda Station for T_e. Temperature of ice surface, T_i, was measured with a platinum resistance thermometer buried at about 2 *cm* depth. Accoring to that, T_i was almost same with air temperature when the latter was below 0°*C* and was maintained at 0°*C* when air temperature above 0°*C*. Of cource, we have some doubts whether foregoing temperatures correctly represent surface values or not. However, more precise values are not always required, because both values are expressed by absolute temperatures, and moreover emissivities are adopted as rough values of 0.9.

Calculated values of Q_i are shown in Table 1 with a summary of basic data.

Table 1. Radiation (*langleys*) in 1971–72 summer season

Period	N	I_s	$s\sigma T_e^4$	I_l	$\alpha_i I_s$	$s\sigma T_i^4$	Q_i
13/Nov.~3/Dec.	5380	11144	11678	8254	4128	11325	3944
3/Dec.~3/Jan.	8294	15709	18794	14678	6552	17931	5904
Total	13674	26853	30472	22932	10680	29256	9848

(*B*) *Evaporation and sensible heat exchange with atmosphere*

Ragotzkie and Likens [1964] carried out evaporation measurements on December 1962 at Lake Vanda. After that observation, the glaciology team of NAZRP and JDVP tried to measure evaporation (ice ablation) by various methods.

One method is to estimate amount of evaporation by change of the lake level. However, this method became useless after the beginning of the inflow from the Onyx River, because the volume of inflow was larger by far than evaporation. If we apply the water balance method to estimating evaporation, the result may include a large error. Thus, this method is available only during the period of no inflow and no precipitation (precipitation is negligible small in this area, especially in the summer season). According to the measurements conducted from 30th of November to 4th of December 1970, total evaporation was 1.4 *cm* expressed by water column. This value (corresponding to 0.35 *cm/day*) is rather larger than that obtained by Ragotzkie and Likens (0.194 *cm/day*) [1964].

Another method is to estimate the evaporation amount from data of ice ablation. A summary of ice ablation measured in 1971–72 season is shown in Table 2. As seen, value in the second period of Table 2 is very large, compared with that of the first period. It may, however, lead to misunderstanding to regard evaporation being also very large in the second period, because the ice surface was very rough and the ice density of the evaporating surface was smaller than that in the previous period.

A third method is to measure weight losses of a certain ice core, but it might also involve error because it is difficult to make a good core sample and to measure the evaporating area.

The fourth and most practical method is to calculate evaporation using meteorological data.

We will assume that the atmosphere on the lake is in neutral or near neutral condition. Moreover, assuming that eddy transfer coefficients for momentum and water vapor are almost the same as usual, then vertical flux of water vapor, that is amount of evaporation from ice surface (F_e), is given by following expression as similar as that from open water surface (see text book),

$$F_e = \frac{0.621}{p} \cdot \rho_a \cdot \gamma_a^2 \cdot u_a \cdot (e_s - e_a), \tag{5}$$

where we will use the following approximation for air drag coefficient γ_a^2,

$$\gamma_a = \left\{ u_a - \frac{\beta g}{T_o} \frac{\theta_a - \theta_s}{u_a} \right\} \frac{k}{u_a} \bigg/ ln \frac{z}{z_o}, \tag{6}$$

where p is atmospheric pressure, ρ_a the density of air, u_a wind speed at height a in meter, e_a water vapor pressure at the temperature of atmosphere θ_a, e_s saturated water vapor pressure at the temperature of the ice surface θ_s, g acceleration of gravity, β an experimental constant (4.5), T_o mean temperature from ice surface to the height of a (°K), z height above the ice surface, z_o roughness length and k the von Karman constant (0.40).

In non-neutral case, i.e. $\theta_a \neq \theta_s$, we have sensible heat exchange (Q_a) between lake ice and atmosphere. We will estimate Q_a by Bowen ratio (R),

$$R = \frac{c_p}{L_1} \cdot \frac{p}{0.621} \cdot \frac{\theta_s - \theta_a}{e_s - e_a}, \tag{7}$$

where c_p is specific heat at constant pressure of air and L_1 is latent heat for sublimation of ice (676 cal/gm).

Because of $\theta_s - \theta_a \leqq 0$ and $e_s - e_a > 0$ at Lake Vanda in summer season, then $R \leqq 0$, and therefore sensible heat may flow from atmosphere to lake ice and take a role of heat gain.

Basic data for calculation of evaporation and sensible heat exchange are SYNOP data of Vanda Station and meteorological data observed by JDVP. Values of θ_a and e_a are those at the height of approximately 1.5 m or so above ground surface, while wind speed was measured at about 10 m height. Therefore, we must deduce the latter to the value at 1.5 m height. The author et. al observed wind speed at 1.5 m height at the lakeside 1.5 km distant from Vanda Station occasionally at the same time of SYNOP data observation.

Fig. 2 shows the comparison between SYNOP data and 1.5 m wind speed, and the mean value of $u_{1.5}/u_{10}$ is 0.46. Assuming the neutral condition, roughness length z_o is calculated as $z_o \fallingdotseq 0.3$ cm by logarithmic law of wind profile. It may be

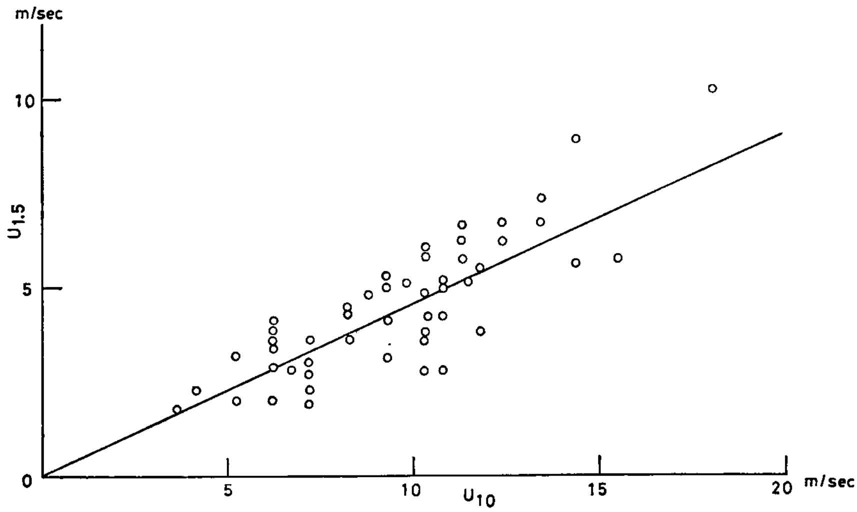

Fig. 2. Comparison between 1.5*m* and 10*m* wind speeds.

interpreted that this value does not express that of the lake ice, but a mean value which includes effects by various surface conditions such as unevenness of the lake ice and/ or ground surface around the lake. However, this value is not so far different from results obtained on a cover of sea ice at the Gulf of St. Lawrence in Canada by Seifert and Langleven [1972]. Watching ice and surrounding ground surface, their unevenness are almost the same scale (about 10 *cm* or so in average), excepting large scale topographic unevenness which may affect larger scale eddy motion of the atmosphere. It is said that the rouhgness length is approximately 1/30 of real unevenness of surface, and then it may be not unreasonable that we regard above values as the average roughness length of the lake ice.

The most reliable value of evaporation by a direct measurement is that in 30th of November to 4th of December 1970 (1.4 *cm* in water column) which was obtained from lowering of the lake level, while the calculated value in the same period is 1.3 gm/cm^2. Thus both values are closely coincide with each other. Calculated values of evaporation (F_e), corresponding heat (L_1F_e) and sensible heat exchange (Q_a) are shown in Table 2 with mean values of Bowen ratio.

Table 2. Ablation, calculated evaporation and sensible heat transfer

Period	h_a	F_e	$L_1F_e(Q_e)$	Q_a	R
13/Nov.~3/Dec.	5.4 *cm*	5.44 gm/cm^2	3677 *lys*	934 *lys*	−0.25
3/Dec.~3/Jan.	13.5	7.83	5293	883	−0.17
Total	18.9	13.27	8970	1817	−0.20

(*C*) *Heat storage and advection*

Change of heat storage of the lake is composed of changes of water and ice temperatures, and heat for melting of the lake ice. Amount of advection is mainly due to inflow from the Onyx River, and inflows from other streams may be negligible small.

Three series of water temperature measurements were conducted at fifteen stations settled on the lake ice in 1971–72 season with a thermister thermometer (Fig. 1); the first measurement was done around 13th of November, the second 3rd of December and the third around 3rd of January. One series of measurements required from four days to one week. As changes of water temperature were recognized in upper layer shallower than about 40 *m* deep, we will calculated change of heat storage in water body in the above mentioned layer.

Ice temperature were observed with platinum resistance thermometers, of which three sensors were buried in the ice at depths of 2, 50 and 100 *cm* respectively, during 26th of November to 7th of January. According to those, ice temperatures of 50 and 100 *cm* depths showed a constant value of $0°C$, and only that of 2 *cm* depth fluctuated slightly. It is thought that ice temperature before above observation period might be lower than $0°C$. However, it is also considered that change of heat storage in the lake ice is much smaller than those in lake water, and then we will neglect this term.

Melting of the lake ice (M) per unit time and unit area will be given by following relation,

$$M=\delta(\rho_i H)-F_e, \tag{8}$$

where ρ_i and H are apparent density and thickness of the lake ice, respectively. Change of heat by melting is given by L_2M (L_2 is latent heat for melting, 80 *cal/gm*). Mean weight of the lake ice per unit area ($\rho_i H$) can be obtained by measuring the distance between the lower surface of the lake ice and the free water surface, assuming the lake ice is floating in lake water and the water included in the ice is continuous with lake water.

The inflow from the Onyx River was measured by the glaciology team of NZARP. It is, however, practical to use data of lake level asending. Inflow per unit time and unit area of the lake (h) will be represented by following expression, putting the density of water as 1 gm/cm^3,

$$h=\zeta+F_e, \tag{9}$$

where ζ is change of lake level, which was estimated by depth sounding data at each observation station, noting that the lake ice did not move during the period. The water temperature of the Onyx River was measured almost every day by NZARP and sometimes by JDVP at the weir settled near the mouth of the river.

Let us consider that the water column of height D_1 and temperature θ_1 changes to that of D_2 and θ_2 after certain a period, being supplied water column of height h and temperature θ_h from inflow.

In this case, sum of change of heat storage and advection are given approximately by the following equation,

$$\left.\begin{aligned} Q_v+Q_f&=D_1(\theta_2-\theta_1)+h(\theta_2-\theta_h)+L_2M \\ D_2&\doteqdot D_1+h \end{aligned}\right\} \tag{10}$$

where effect of melt water is neglected because M is much smaller than D_1 and h.

First and second terms of the right hand side in Eq. (10) involve two effects, i. e. change of heat storage of lake water and advection by the river, but it is not so easy to separate them into storage and advection respectively. Tables 3 and 4 show basic data and results.

Table 3. Data for calculation of heat storage and advection

Date	Height of water column	Water temperature	$\rho_i H$	ζ
13/Nov.	3663 *cm*	6.51°*C*	337 *gm/cm*^{2}	0 *cm*
3/Dec.	3704	6.74	324	28
3/Jan.	3742	6.86	309	51

Table 4. Heat storage+advection (Q_v+Q_f)

Period	h	θ_h	M	$D_1(\theta_2-\theta_1)+h(\theta_2-\theta_h)$	L_2M	Q_v+Q_f
13/Nov. ~ 3/Dec.	33.4 *cm*	1.8°*C*	7.6 *gm/cm*^{2}	1007 *lys*	608 *lys*	1615 *lys*
3/Dec. ~ 3/Jan.	30.8	1.4	7.2	613	576	1189
Total	64.2		14.8	1620	1184	2804

(*D*) *Conduction through the bottom of the lake*

Ragotzkie and Likens [1964] also measured temperature gradients in the soil of the lake bottom. From those results, they estimated the amount of heat flow to be 44 *lys/day* upward through the bottom, while the total heat gain was estimated as 154 *lys/day*. Thus the heat by conduction takes a great part of heat gain.

According to the water temperature measurements in 1970–71, the deeper we went, the smaller the water temperature gradient became; and moreover it was recognized that the maximum temperature (25°*C*) appeared at several meters above the lake bottom, and then the bottom temperature somewhat decreased to 24.7–24.8°*C*. Fig. 3 shows the figure of water temperature profile observed in 1970–71.

This fact is incompatible with the claim of Ragotzkie et. al, and means that heat is flowing out from the lake through the bottom. For comparison with their result and verification of the direction of heat flow, soil temperature was measured by a thermister thermometer driven into the bottom at some points. It was seen that soil temperatures at all points were 0.2–0.3°*C* lower than the bottom temperature.

Thus, heat flow out of the lake through the bottom is estimated as 0.1 *lys/day*

Fig. 3. Temperature profile at Station K on 2 January 1971.

from water temperature gradient assuming molecular diffusion process based on the fact of the strong density stratification of water, or less than 3 *lys/day* from the soil temperature gradient which may be less than 0.3°*C*/20 *cm*. However, these values are very small compared with values of other terms in the heat balance equation.

(*E*) *Heat balacnce in the lake*

The heat balance in Lake Vanda in summer season can be established by foregoing estimations, and Table 5 shows the result in 1971–72. In the period of 13th of November to 3rd of December, heat loss+storage is a little larger than heat gain. This may be caused from over-estimation of evaporation, because the ice surface was smooth in the earlier stage of this period, and then the value of z_0 might be somewhat smaller than 0.3 *cm*.

On the contrary, heat gain is a little larger than heat loss+storage in the period of 3rd of December to 3rd of January, and both mean values in the whole period coincide well with each other.

Thus it is concluded that factors of heat gain are composed of two processes such as net flux radiation and sensible heat exchange with the atmosphere, and the main part of them being consumed for evaporation and the residues accumulated in the lake.

The result obtained here is quite different from that of Ragotzkie et. al, especially on the interpretation of heat gain. It is thought that the effect of conducting heat through the lake bottom does not take an important role for maintaining the present water temperature, whether it is positive or negative.

Table 5. Heat balance in Lake Vanda (*lys/day*)

	Heat gain			Heat loss+storage+advection		
Period	Q_i	Q_a	Q_i+Q_a	Q_e	Q_v+Q_f	$Q_e+Q_v+Q_f$
13/Nov.~3/Dec.	197	47	244	184	81	265
3/Dec.~3/Jan.	190	28	218	171	28	209
Total	193	36	229	176	55	231

3. Consumption of solar radiation and heat flux in the lake

In the previous section, we have found that the heat gain of the lake consists of solar and sky radiation and sensible heat transfer from the atmosphere. Because the temperature in the lake ice was maintained at 0°C throughout the whole period, there is no heat flow by conduction, and then Q_a will be consumed for the phenomena at the ice surface such as evaporation and back radiation. Therefore it is considered that only solar radiation affects the melting of lake ice and rising of water temperature in the lake.

The amount of melting presented in Table 4 must be separated into two parts, i. e. internal melting in the ice and melting at the lower surface of the ice. The former may be caused from heat generation by absorption of solar radiation, while the latter may involve the direct effects of solar radiation and heat transfered from lake water.

The melting at the lower surface of the ice in a certain period (h_m, expressed by height of ice column) is given as:

$$h_m = \Delta H - h_a, \tag{11}$$

where ΔH is decrease of ice thickness and h_a is ice ablation in the same period.

For example, in the period of 13th, November to 3rd, January, ΔH was 22.0 *cm*, and ablation was 18.9 *cm* (see Table 2), then h_m is calculated as 3.1 *cm*. This is corresponding to 2.84 gm/cm^2, and the heat for melting is 227 *lys* ($5.1 \times 10^{-5} lys/sec$), assuming the density of ice 0.917 gm/cm^3. Consequently, internal melting is calculated as about 12.0 gm/cm^2 (960 *lys*).

As solar radiation which is absorbed in this ice column of 3.1 *cm* height is much smaller than the above value, the main part of that must come from below. Also this heat can be interpreted as a feedback of solar radiation absorbed in lake water. Thus it is considered that solar radiation penetrated through the lake ice is the sum of heat storage change of water and heat for melting at the lower surface of the ice, and that is calculated as 1844 *lys*.

Finally, total solar radiation were consumed as follows; reflection 39.8%, internal melting 3.6%, penetration through the lake ice 6.9%, and evaporation and back radiation 49.7%. Table 6 summarizes the consumption of solar radiation in our observation period.

Table 6. Fraction of consumption of solar radiation

Period	Reflection	Internal melting	Penetration	Evaporation and back radiation
13/Nov.~3/Dec.	37.0 %	4.7 %	9.8 %	48.5 %
3/Dec.~3/Jan.	41.7	2.8	4.8	50.7
Total	39.8	3.6	6.9	49.7

Using the heat flux (q) at the lower surface of the ice, the apparent heat transfer coefficient in the upper layer will be estimated as follows

$$\kappa = \frac{q}{\rho c} \Big/ \frac{\Delta\theta}{\Delta z}, \tag{12}$$

where $\Delta\theta$ is a difference between the temperature at the top of the lake water ($0°C$) and that of the main convecting layer (around $7.5°C$), Δz is the height of water

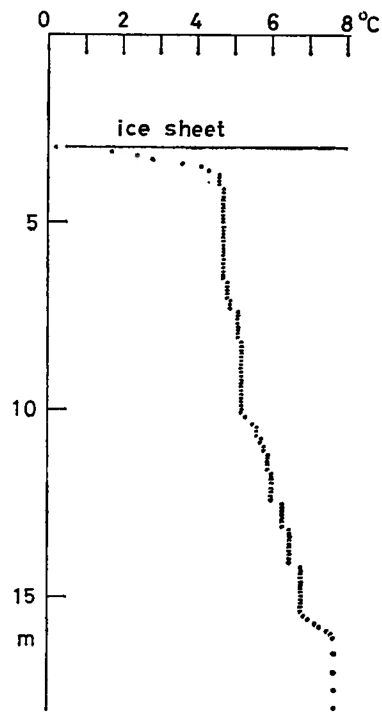

Fig. 4. An example of step-like structure of water temperature profile observed at Station A on 4 January 1972.

column considering here. As the mean value of $\Delta\theta/\Delta z$ is 6.0×10^{-3} *deg/cm* and q is 5.1×10^{-5} *lys/sec*, κ equals to 8.5×10^{-3} *cm²/sec*, which is about six times as large as molecular diffusivity.

It may seem that this value has a relationship with the step-like structure of temperature profile shown in Fig. 4. It is thought that physical properties such as heat and salinity are transported by convective motion in layers of uniform temperature. On the contrary, the transfer process in sheets, in which sharp gradient of temperature are observed, may be due to molecular diffusion. Thus we can regard the step-like structure as composite media composed of many layers and sheets which have various diffusivities. If heat does not generate in water body and the steady state is established, the apparent diffusivity κ for the medium, whose thickness is D, will be expressed by following relation as well-known,

$$\left.\begin{aligned}\frac{D}{\kappa}&=\frac{\Delta z_1}{\kappa_1}+\frac{\Delta z_2}{\kappa_2}+\cdots+\frac{\Delta z_n}{\kappa_n},\\ D&=\Delta z_1+\Delta z_2+\cdots+\Delta z_n,\end{aligned}\right\} \tag{13}$$

where Δz_i and κ_i are thickness and diffusivity of each layer or sheet, respectively. Though the upper layer of Lake Vanda has heat generation by solar radiation, and is not in the steady state, let us apply Eq. (13) to the lake as a rough approximation.

Expressing diffusivity in uniform temperature layers as κ_c and molecular diffusivity as κ_m, and putting the total thickness of all sheets as δ, we obtain

$$\frac{D}{\kappa}\sim\frac{D-\delta}{\kappa_c}+\frac{\delta}{\kappa_m}. \tag{14}$$

We can regard that the value of κ_c is sufficiently large, and then we get the following:

$$\frac{\kappa}{\kappa_m}\sim\frac{D}{\delta}. \tag{15}$$

According to the observation in January 1972 (see Fig. 4), D and δ were 1300 and 290 *cm* respectively. Therefore, we get the value of κ/κ_m about 4.5. As the water temperature was measured at intervals of every 10 *cm*, thickness of δ may be estimated largely, and so κ/κ_m may have somewhat larger value.

However, values of κ/κ_m obtained here by two different ways seem to be in good agreement, and the result gives a physical meaning for an apparent diffusivity.

4. Summary and discussion

From the evaluation of heat balance in Lake Vanda during 1971–72 summer season, it has become clear that heat gain of the lake consists of solar and sky radiation and sensible heat exchange with the atmosphere, and effects of geothermal or hydrothermal activities are not expected. Also, a thermal dome could not be found by detailed temperature measurements. It was one of the marked features that isothermal and isohaline lines showed horizontal distributions. If there are some geothermal activities, they may have only protection effects for out-flowing of heat accumulated in the lake by solar radiation. For clarifying the situation, it is required to measure the underground temperature till appreciably deep parts.

It was also presented that an aerodynamical method would be useful for estimation of evaporation from the lake ice, and the annual evaporation is estimated as some 50 *cm* on the basis of meteorological data observed by winter and summer members of Vanda Station. Annual average inflow from the Onyx River since 1968 was about 6.8×10^6 $m^3/year$ (measured by NZARP). Assuming that the lake level will be fundamentally determined by the balancing between annual evaporation and supply from the Onyx River, about 2.6 times area of the present lake area will be necessary for balancing with above inflow. As it is said that the maximum lake area in the past had been about 2 times of the present one, this volume of inflow is sufficient for maintaining the lake in the time of the ancient lake level remained at about 60 *m* above the present lake level. This is interesting from the viewpoint that change of lake level is an important criterion for climatic change.

An apparent heat transfer coefficient at the upper layer of the lake in 1971–72 season was about 6 times larger than molecular coefficient, but it can never be said that this value is always maintained.

The value of κ/κ_m in the previous season was very large-up to around 50, calculated from the melting of lake ice at the lower surface, 15 gm/cm^2 (1200 *lys*) during 2nd of January to 3rd of February 1971. Such a large value would be caused from stirring of water by lake ice motion which occured by blowing, because wide open-water-area appeared in that season. Therefore, the value in 1971–72 season may be near minimum one observed at the time of no lake ice motion, and average value of κ/κ_m would be probably some 20 or so. Using this value with other necessary properties, we see a possibility that the present temperature of the lake water can be explained by solar radiation without heat supply from geothermal activity (Yusa [1971]).

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